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Temperature Monitoring and Overhang Layers Problem

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Abstract

The principles of measuring the surface temperature of powder bed in the focal spot of the laser radiation while scanning the surface using galvoscanner with F-teta lens have been designed. The optical system provide the possibility to measure spatial distribution of brightness temperature at two wavelengths and selected temperature profiles, calculation of colour temperature and maximum temperature in focal spot . Investigation of the sintering of overhang layers has been conducted under temperature monitoring and Rayleigh - Taylor instability of the contact surface between melt and loose powder in a gravity field was found.

Keywords: powder bed; surface temperature; overhang layer; instability

1. Motivation

Growing demands on the quality of sintered product require reliable methods to monitor and optimize the sintering process.In most papers the evolution of the optical emission from the melt in one or more spectral range was recorded and the process was monitored from the level or character of the optical signal. However for the precision control of the SLS/SLM processes the measurements of the main parameters of these processes – maximum surface temperature, temperature distribution in the processing area , size of the melt and control their evolution are necessary. The system was developed [1, 2] for monitoring of temperature distribution in laser irradiation zone based on registration using a high speed digital CCD – camera and maximum temperature measurements in laser spot by pyrometer. Using a calibrated pyrometer and camera allows to fully control the process of sintering/ melting. Also the principles of measuring the surface temperature of powder bed in the focal spot of the laser radiation while scanning the surface using galvoscanner with F-teta lens have been designed [3]. The developed optical monitoring system has been used in studies of sintering of the overhang layers and the results of studies are presented in this paper.

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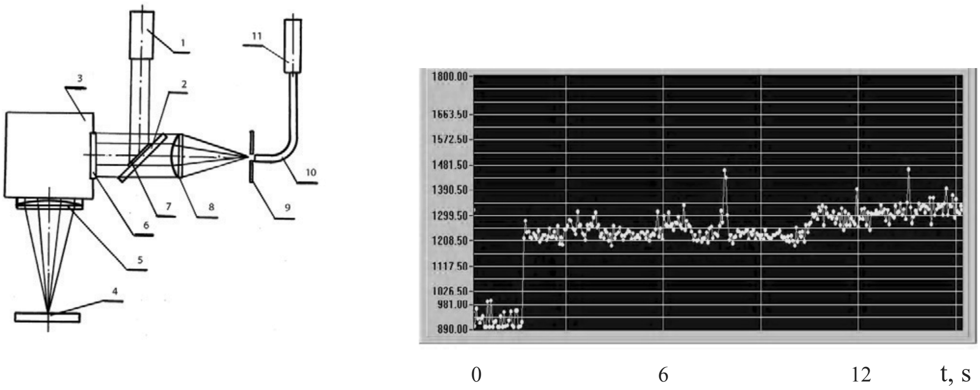
2. Method and apparatus of temperature measurements

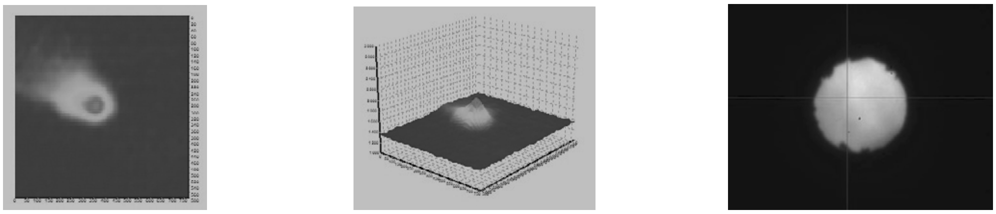
The most-used galvo scanner systems have a selective character of reflection depending of wavelength and angle of rotation , that must be take in account in deciding on a spectral range of temperature measurements. Also custom made F- teta lens are not achromatic usually. That cause image shift in coaxial set-up sensor positioning systems between the laser focus spot and its image at a wavelength different from the laser one. This shift increases with the distance from the center of powder bed which leads to measurement errors if the temperature measurement is carried out correctly that is in a small region of the laser spot in the area of 20 - 100 microns. 2 D sensors are more tolerant to such shifts and this is its major advantage over single spot sensors. But for the continuous control of melting process the measurement of maximum surface temperature in the heat affected zone is preferable and more for manufacturing facilities. In principle, the F-teta lens can be colour corrected but only at a single wavelength and this greatly increases the price of the lens. Also standard scanner mirrors have the reflection ban**d** with width of about 250 nm centered at a wavelength of the laser and measurement outside this band leads to large losses in the sensitivity of the measurements. The principles of measurements was devised [3] and special optical scheme was designed to minimize image shift . Measurements are carried out at wavelengths close to laser wavelenght which are prominent using a gradient type dichroic mirrors and filters (fig.1a) .



a. b.

Figure 1. (a) Scheme of temperature measurements by pyrometer: 1- laser, 2- gradient mirror, 3- scan head, 5- F-teta lens, 6- powder bed, 7- dichroic mirror, 8- lens, 9- diaphragm, 10 – fiber. 11- pyrometer; (b) Pyrometer output in ^{0}C on the PC screen under laser melting of Inox plate. Spot size – 100 μm, spot speed 100 mm/s, laser power 80W ;

A two-wavelength pyrometer 11 (fig.1a) with time resolution 50μs and spatial resolution 50 μm based on two InGaAs photodiodes register the surface thermal radiation on two wavelengths in the range 900- 1200 nm. The image of scanning area with diameter 130 μm render on fiber diaphragm 9 diameter of which 100 μm fix area of signal integration. The photodiodes signals are amplified ($k = 10^6$) and gated with the variable frequency and gate duration. The maximum brightness and color temperature in the sintering zone are displayed (fig. 1b).



a. 100 µm b. c.

Figure 2 (a) Spatial distribution of thermal radiation intensity at the irradiation spot in selective laser melting. Powder-W. Laser spot size -100 µm; scan speed -100mm/s, (b) Spatial profile of recalculated brightness temperature at the irradiation spot. (c) CCD imaging of the lamp diaphragm during calibration.

The system for monitoring temperature distribution in laser irradiation zone based on high speed digital CCD - camera has been used . The image of the melting zone with a five time magnification is projected onto the matrix plane of digital CCD camera and spatial brightness temperature distribution is determined (fig. 2a,b) .

Simultaneous monitoring of the melting process with a videocamera recording the temperature distribution on the surface and pyrometer enables to correlate the detected 1D-signal with real geometry of the melt.

All temperature sensors calibration is performed by using a W- halogen lamp with a transmitting diffuser. Lamp diaphragm 1mm in diameter is housed in the laser spot at powder bed (fig.2c). Previously lamp was calibrated with a black body model in the temperature range 1200- 1800^0K. Nonuniformity of the temperature distribution over the area of the diaphragm does not exceed 5 K.

3. Experimental

SLM technology has difficulties in building an overhange plane due to the process definition of layered wise production in a powder bed. Some of the processes can solve this problem by using support structure which afterwards has to be removed by post processing. Another way consists in investigation of the this phenomena and control of the melting process[4].

In this study the PM 100 machine of Phenix Systems with the typical for this kind of equipment design was used. This system allows to manufacture parts from metallic and ceramic powders within a cylindrical volume of 100 mm diameter and up to 100 mm in height. The source of radiation is a YLR-200 cw fiber laser manufactured by IPG Photonics with a maximum power P = 200 W, the wavelength λ = 1075 nm and the laser spot size d = 100 µm.

In these experiments, a some layer of Cu, CoCr and W powder 25 – 50 µm in diameter was deposited using a usual powder feeding system (a scrape blade). The thickness of loose powder bed was 3 mm. The powder was then laser processed using Phenix machine with galvo scanner ScanLab - 14 . Overhang layers are scanned by laser spot with diameter 100 µm and scan shift 30 µm under temperature control. Only one cross- section 100 x 100 mm is scanned with the scan speed 100 mm/s. Experiments was conducted in N_2 and Ar atmosphere.

The brightness temperatures resulting from experiments (fig.2b, fig. 3) have been transformed to thermodynamic temperatures using emissivity data: for Cu - ε = 0.1 [5] ; W- ε = 0.3 [6]; CoCr - ε = 0.35 .

Due to heat transfer to powder bed a surrounding powder has been sintered. The brush has been used to remove excess powder as best as possible.

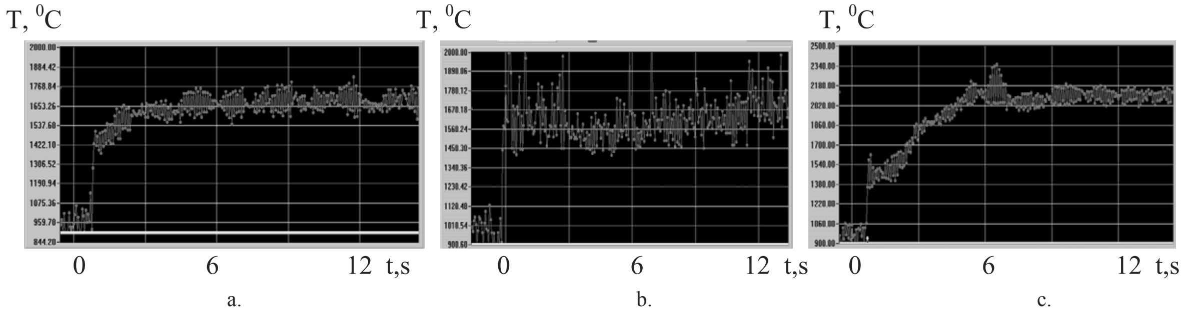


Figure 3. Brightness temperatures in melted area: (a) – CoCr , 50W; (b) – Cu, 80W; (c) – W, 50W.

4. Results and Discussion

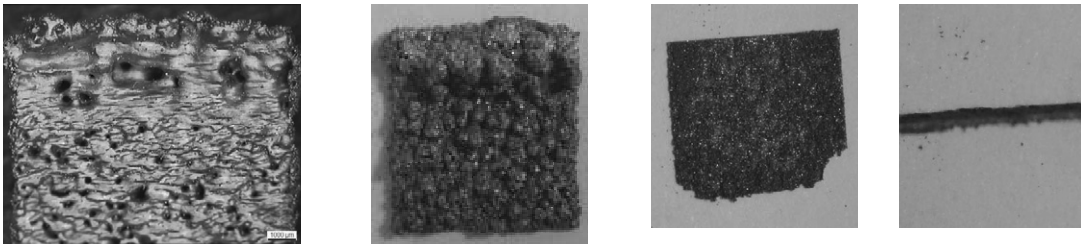
As known [7] the effective thermal conductivity of loose metallic powders is controlled by gas in the pores. Therefore, it is essentially independent of material but depends on the size and morphology of the particles and the void fraction, as well as on the thermal conductivity of the gas. For 10–50 μm powders the effective thermal conductivity is typically from 0.1 to 0.2 W/(m K) in air at room temperature [7].

At loose powder bed, the heat conduction rate may be more than 10^2 - 10^3 times smaller than the bulk conductivity . This results in too large heat input during scanning of an overhanging layer, thick melt pool formation , which sink in the powder bed . Mechanism of the melt penetration into loose powder bed has not been investigated and threshold conditions have not been uniquely determined.

As established in current experiments accumulation of heat in the layer affects the flow of the sintering process, encouraging the development of the instability of the contact surface between the melt and powder in a gravity field. Observed structures on the contact surface between melt and powder (fig.3,4) are typical of the Rayleigh - Taylor (RT) instability [8]. An assessment of the instability of RT in the experimental conditions, when the layer of molten metal is located on a layer of powder with a density of ~ 0.5 of the melt. Most intensively will rise perturbations with a wavelength $\lambda m = 4\pi (\alpha \nu 2 / g)^{1/3}$ equal cm.

Linear increment $\tau = (g \cdot 2\pi / \lambda)$ 1 / 2 of perturbations growth is 3· 102 1 / s.As shown in the early stages of the process falls in the nonlinear regime, which probably leads to the observed structures with a characteristic size of 1 mm and more (Fig.4). Small thickness of the melt leads to the formation of hollow conical spikes and pores on the surface (Fig.4 c). At the end of the scanning area, there is complete loss of stability of the molten layer with a dip to the loose powder (fig. 4). The maximum surface temperature during melting of Cu layer reached 1900^0K- 2100 ^{0}K and melt thickness reached 1mm. In such conditions the melt boiling is absent and recoil pressure can not cause melt pool sink into the loose powder bed [9].

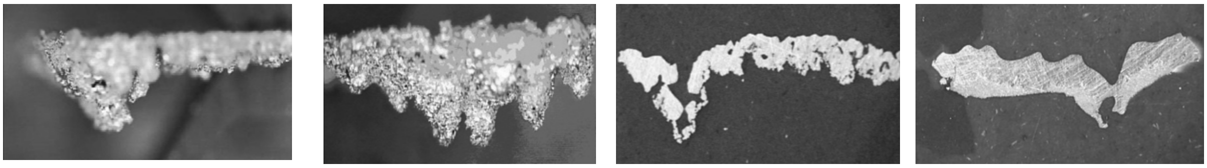
The maximum surface temperature during sintering of W layer did not exceed 2900^0K, that is consistent with the regime of selective laser sintering . Lack of sufficient melt layer prevented the development of instability (fig.4c,d).



2 mm 2 mm 2 mm

a. b. c. d.

Figure 4. Structure of overhang layer. (a) – top view, (b) – bottom view, (c) – side view. Powder – Cu, 50 µm, P = 80W, scan speed – 100 mm/s, laser spot - 100 µm, shift - 30 µm. (c,d) - powder – W, 25 µm , P= 85W; scan speed – 100 mm/s , laser spot - 100 µm, shift - 30 µm.



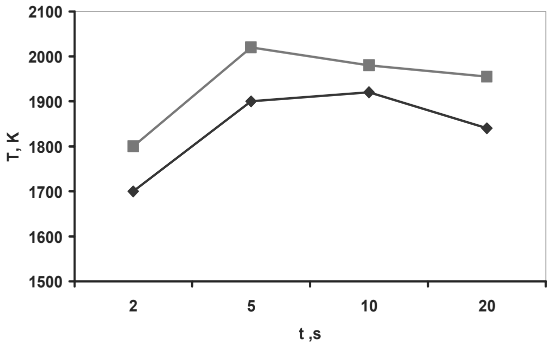
2mm 2 mm 2 mm 2 mm

a. b. c. d.

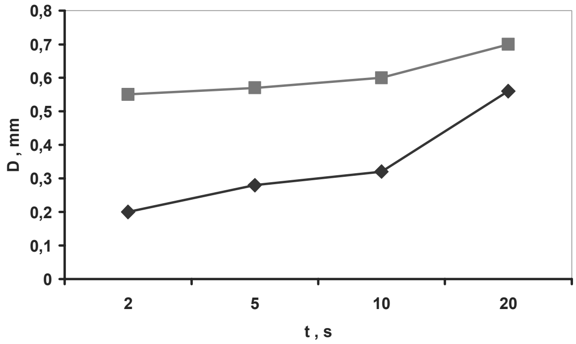
Figure 4. Structure of overhang layer. (a) – side view, (b) – end view , (c) – cross-section. Powder – Cu, 50 µm, P = 80W . (d) – cross-section. Powder – CoCr,25 µm , P = 80W. Scan speed – 100 mm/s , laser spot - 100 µm, shift - 30 µm.

The measurements of the maximum melt temperature in area 130 µm in diameter by pyrometer in combination with the measurements of the temperature distribution by CCD-camera were conducted. It has been found that temperature deviation (fig. 5a) while the melt is expanding at scan area end are of a minor nature . Probably this effect may be linked to heat removal growth into the loose powder bed with increasing melt size, that the opposite situation may occur – temperature fall (fig.5a).

At the same time the growth of the melt region in the laser spot area was observed (fig.5b). This increase results from the accumulation of heat in the molten layer and high thermal conductivity of the melt.



a.



b.

Figure 5. (a)- Maximum brightness temperature in melt during scanning of the overhang area (□ – CoCr , ◊ - Cu). (b) – Diameter of melt zone , level- 1500 ^{0}K (□ – CoCr , ◊ - Cu).

5. Conclusion

The principles of measuring the surface temperature of powder bed in the focal spot of the laser radiation while scanning the surface using galvoscanner with F-teta lens have been designed. The optical system provide the possibility to measure spatial distribution of brightness temperature at two wavelengths and selected temperature profiles, calculation of colour temperature and maximum temperature in focal spot. Investigation of the sintering of overhang layers has been conducted under temperature monitoring.

As established in current experiments accumulation of heat in the molten overhang layer result in the development of the instability of the contact surface between the melt and loose powder in a gravity field. Observed structures on the contact surface between melt and the loose powder are typical of the Rayleigh - Taylor (RT) instability.

RT instability progress causes the complete loss of stability of the molten layer with a dip to the loose powder bed.

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